Technology Demonstration Mission (TDM)
Cryogenic Propellant Storage & Transfer (CPST)

CPST Project Overview and Cryogenic Activities

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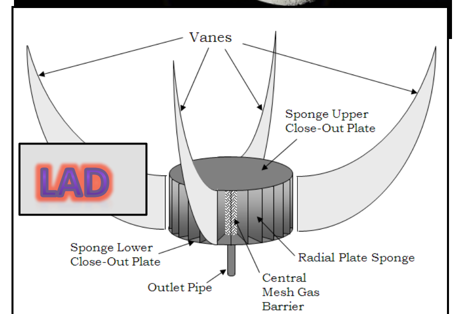
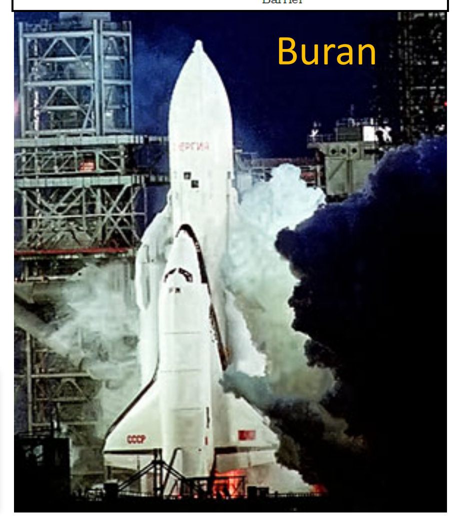
Present Challenges for In-Space Cryogenic Systems

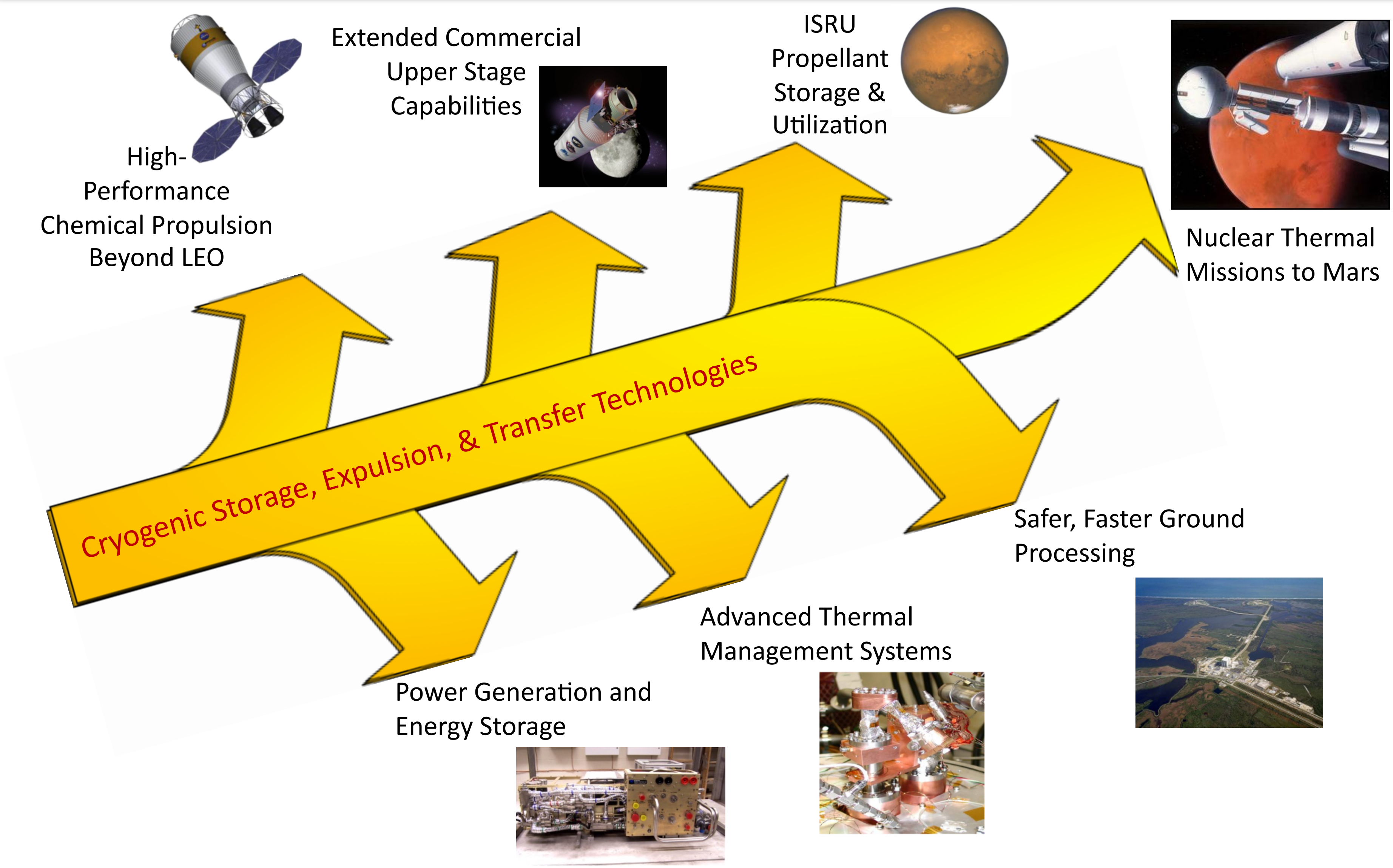
- We have no demonstrated capability to store cryogenic propellants in space for more than a few hours
  - SOA is Centaur's 9 hours with boil-off rates on the order of 30% per day
- We have no demonstrated, flight-proven method to gauge cryogenic propellant quantities accurately in microgravity
  - Need to prove methods for use with both settled and unsettled propellants
- We have no proven way to guarantee we can get gas-free liquid cryogens out of a tank in microgravity
  - Gas-free liquid is required for safe operation of a cryo propulsion system
  - Need robust surface-tension **liquid acquisition device (LAD)** analogous to those in SOA storable propulsion systems
  - Only known experience in the world is the single flight of the Russian Buran single flight (liquid oxygen reaction control system)
- We have no demonstrated ability to move cryogenic liquids from one tank (or vehicle) to another in space

A flight demonstration with cryogenic propellant storage, expulsion, and transfer can remedy these problems (*and other more subtle ones*)!





CPST TDM Offers Cross-Cutting Benefits



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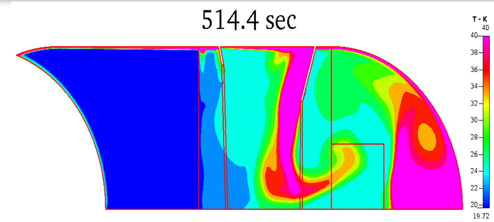
Why Is Microgravity Required for CPST?

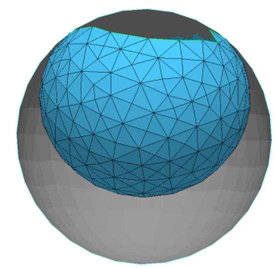
- Passive and active thermal control performance is unknown due to effects of acceleration level and propellant orientation.
  - Mixing of liquid (and heat transfer) inside the tanks
  - Low-g effects on internal convection and on thermal gradients
  - Analytical models for cryogenic storage tanks must be correlated to low-g data

- Liquid Acquisition Device (LAD) only works when surface tension forces are greater than gravity/acceleration forces.
  - Need long-duration microgravity to demonstrate LAD robustness across range of conditions and operating scenarios.

- Propellant Mass Gauging must be demonstrated in microgravity in an actual tank across a range of propellant orientation scenarios and fill levels.



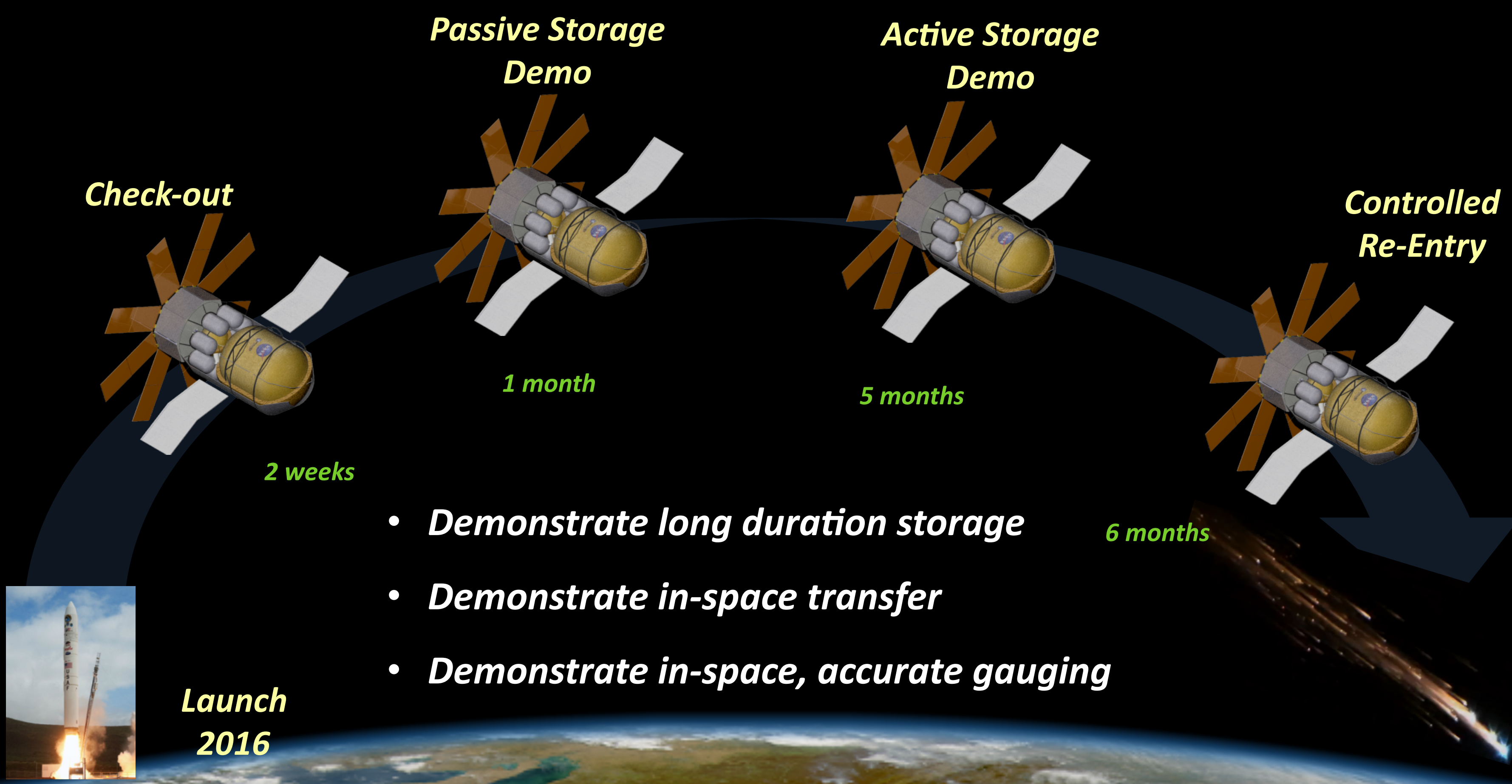
CFD Model of Ullage Temperature of Saturn IV-B in Microgravity


Fluid interface at 30 micro-g settling thrust in a 36” diameter LH2 tank at 50% fill (CPST POD transfer tank). A level sensor in the center of the tank would incorrectly read around 27% fill.


Mass Gauging Low-g aircraft test

Cryogenic Propellant Storage and Transfer Technology Demonstration Mission

NASA is undertaking a demonstration mission to advance cryogenic propellant storage and transfer technologies that will enable exploration beyond Low-Earth Orbit



- *Demonstrate long duration storage*
- *Demonstrate in-space transfer*
- *Demonstrate in-space, accurate gauging*

CPST Technology Demonstration Overview

Needs

Create the innovative new space technologies for our exploration, science, and economic future

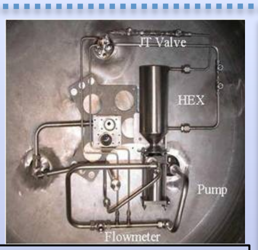
Goals

Advance cryogenic propellant systems technologies for infusion into future extended in-space mission

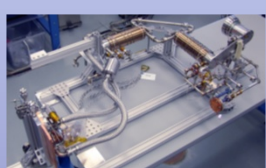
Objectives

- Store cryogenic propellants in a manner that maximizes their availability for use regardless of mission duration
- Efficiently transfer conditioned cryogenic propellant to an engine or tank situated in a microgravity environment
- Accurately monitor and gauge cryogenic propellants situated in a microgravity environment

Technologies



TVS components (installed in test tank)



Turbo Brayton cryocooler

LH2 /LO2 Storage

Technology	TRL
Passive storage: thick MLI and reduced penetration heat leak	4/6*
Passive storage: low conductivity structural attachments	4/6*
Active thermal control: Broad Area Cooling (tubes on tank or tubes on shield)	4
Active thermal control: cryo-coolers (90K)	6
Tank Pressure Control: thermodynamic vent system (TVS)	5
Tank Pressure Control: mixing pumps	5

LH2 /LO2 Acquisition

Technology	TRL
Liquid Acquisition Devices (LADs)	4/5*

Screen Channel Capillary LAD

LH2 /LO2 Transfer

Technology	TRL
Transfer Valves	4/5*
Transfer Pump**	5
Line and Tank Chill-down	5

LH2 /LO2 Quantity Gauging

Technology	TRL
Advanced Wet-Dry Sensor	4/5*
Radio Frequency (settled/unsettled)	5

RF Gauge Test Rig

- Where TRL has two values they are for LH2/LO2
- Flight or ground test program to mature technology

**Ground test only

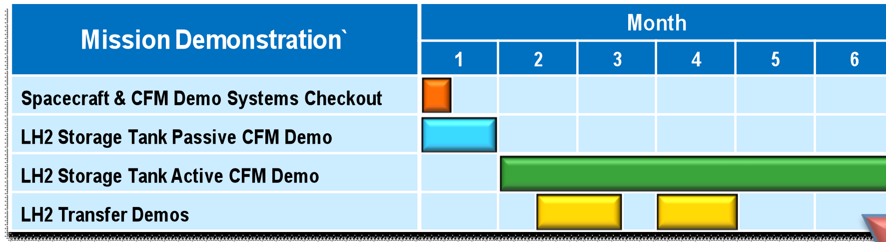
Program Level Requirements

- CPST-PROG-1 Demonstration of Propellant Storage
  Thermal conditioning of cryogenic propellants in microgravity in a manner extensible to long-duration storage in full-scale space systems shall be demonstrated.
- CPST-PROG-2 Demonstration of Propellant Transfer
  Delivery of bubble-free cryogenic propellants in a manner extensible to full-scale space systems via transfer in microgravity without prior settling shall be demonstrated.
- CPST-PROG-3 Critical Scaling Data for Liquid Oxygen
  Performance data necessary to address all critical scaling issues related to long-duration storage of liquid oxygen in microgravity with zero boil-off shall be obtained.
- CPST-PROG-4 Critical Scaling Data for Liquid Hydrogen
  Performance data necessary to address all critical scaling issues related to long-duration storage of liquid hydrogen in microgravity with an average boil-off rate of less than 0.05% (TBR) per day shall be obtained.
- CPST-PROG-5 Development of Performance Models
  Performance models suitable for designing full-scale space systems that store cryogenic propellants for long durations shall be developed.

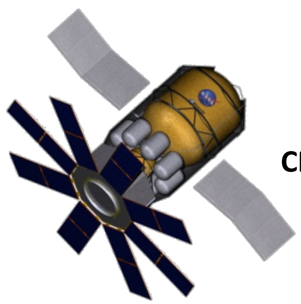
Conceptual Scenario for a CPST Mission Architecture

Cryogenic Fluid System
- LH2 Storage
- CFM management
- Transfer Demonstration System
- Data Recording

Six Month Orbital Mission

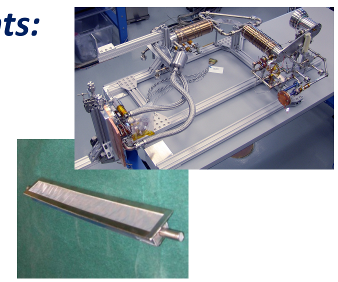


Spacecraft Bus
- Attitude Control
- Communications
- Propulsion



CPST TDM

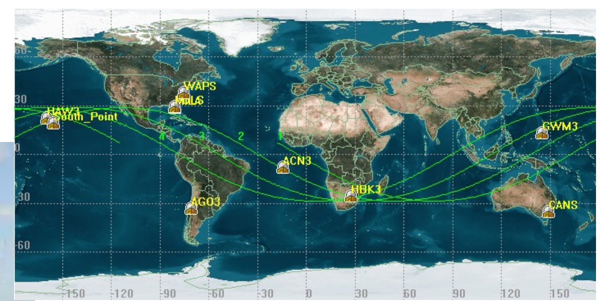
Technology Developments:
- **Tank Thermal Control**
- **Tank Pressure Control**
- **Cryogenic Fluid Transfer**
- **Liquid Acquisition**
- **Mass Gauging**
- **Leak Detection**



Controlled Reentry & Disposal

Launch Site: TBR

Mission Operations



Communications: Near Earth Network

CPST Acquisition Description

- Project Unique RFP/Single Prime with GFE of Cryogenic Fluid System (CFS) Payload
  - NASA retains project management and principal investigator responsibilities
  - NASA will design, develop, integrate, and test the CFS payload and provide as GFE to a prime contract
    - Design and development of an integrated CFS
    - Procurement of some technology components (pumps, cryocooler, struts, eg)
    - Design and development of the CFS payload structure
    - Integration of all technology components
    - Design and development of avionics for command and control of the CFS payload
  - NASA will provide technology maturation, GTA, and modeling/analytical capability
  - NASA performs insight/oversight of contractor implementation of the balance of mission
  - Baseline approach to procure Launch Vehicle through Launch Services Program (LSP)
  - Prime contractor is responsible for balance of the mission, including integration of the CFS payload with the spacecraft bus

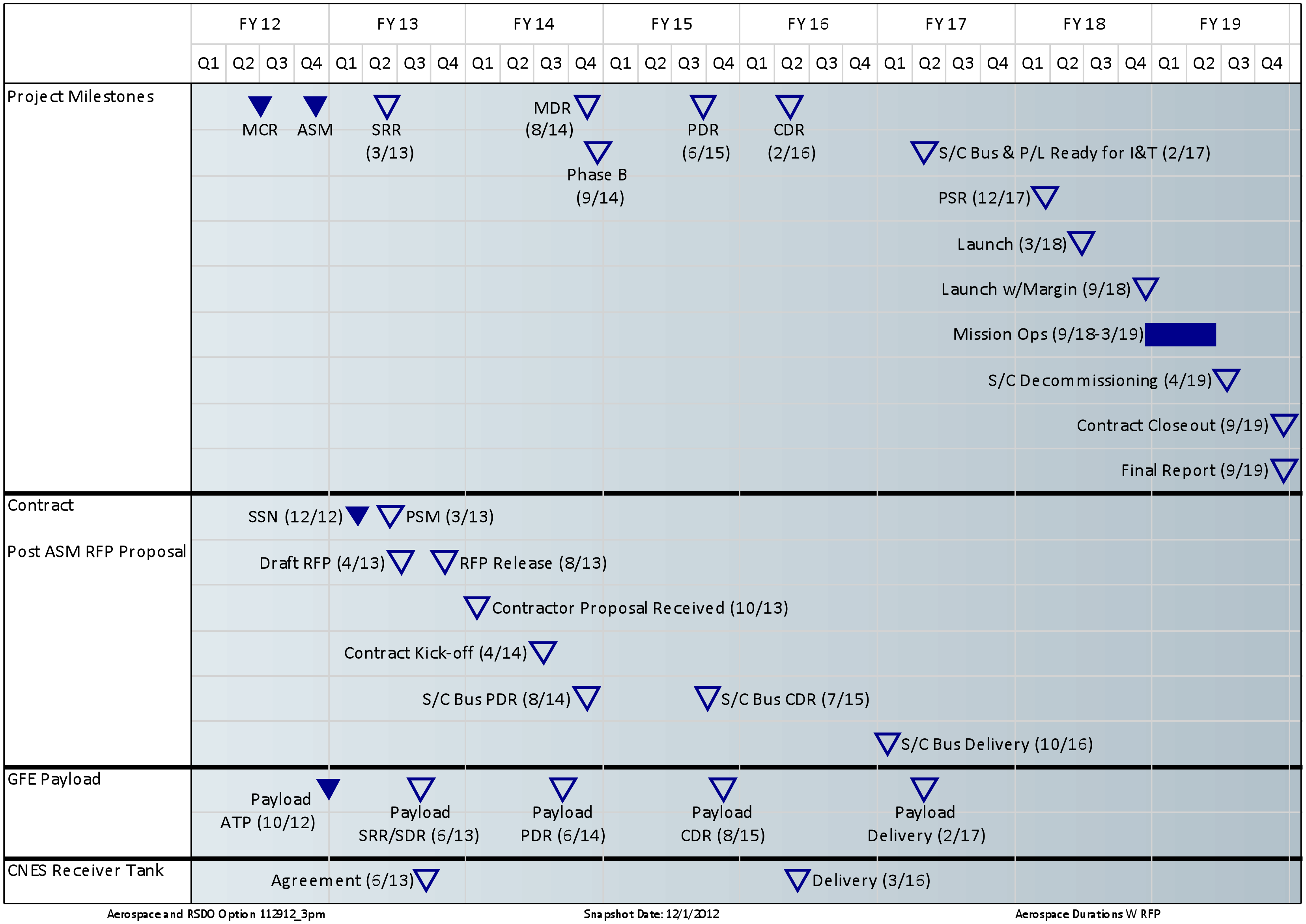
Implementation Strategy

- In-house payload development to be delivered to a prime contractor responsible for balance of mission
- In-house payload development includes:
  – Protoflight hardware development of the cryogenic fluid system (CFS), and associated GSE
  – Assembly, integration, and test of the CFS payload for delivery to the prime contract for spacecraft integration
  – Ground loading requirements and concept development:
    - Likely pad-loaded concept
    - Supplied by the launch vehicle provider
  – Technology operations
    - Interface with mission operations
    - In-house development

Procurement for Balance of Mission

- Single RFP approach was chosen based upon trades.
  - With no schedule benefit, the RFP approach was chosen over RSDO as being less risky due to minimal interfaces
- Sources Sought Notice released 11 December 2012
  - Kick-off to procurement process
  - Required for approval of the procurement strategy
- Procurement Strategy Meeting at NASA HQ in March 2013
- Draft RFP release in April 2013
  - Industry input ahead of the Payload SRR
- Final RFP release in August 2013
  - Aligns with Payload SRR
  - Final RFP has input from industry as well as the SRR Board

CPST Top-Level Milestone Schedule



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Background on CPST Technology Activities

Three categories of testing:

- **Technology Maturation:** Raising the TRL of technologies planned for the flight demonstration to reduce the flight development risk.
- **Integrated Ground Testing:** Testing multiple technologies at once to identify unexpected interactions that might impact performance.
- **Ground Demonstration:** Demonstration of technology/capability on the ground in parallel with the flight demonstration to to achieve broader (more comprehensive) demonstration scope at lower cost.

In addition, development and validation of analytical tools/modeling focused on CFM technology and capability are a critical aspect the CPST TDM.

Summary of Tech Maturation/Integrated Ground Test

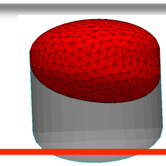
Test Name	Objective
LH2 Active Cooling – Thermal Test	Demonstration of a flight representative active thermal control system for Reduced Boil-Off (RBO) storage of LH2 for extended duration in a simulated space thermal vacuum environment
Broad Area Cooling Shield/MLI Structural Integrity	Assess the structural performance of an MLI / BAC shield assembly subjected to launch vibration loads
LAD Outflow & Line Chill	Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow
Penetration Heat Leak Study	Measurement of heat leak due to struts penetration integrated with MLI.
Active Thermal Control Scaling Study	Conduct study to show relevancy of CPST-TDM active thermal control flight data to full scale CPS or Depot application
Thick MLI Extensibility Study	Assess optimum approach for attachment of thick (40-80 layer) MLI to very large tanks
Analytical tools	Continue development of tools specific for CPST
Pathfinder Integrated System Test (GTA)	Demonstrate flight-scale system operations & interactions; demo tank mfg; early software dev.

Ground Demonstration

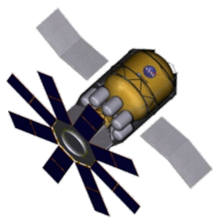
Test Name	Objective
LO2 Zero Boil-off	Demonstration of a flight representative active thermal control system for Zero Boil-off (ZBO) storage of LO2 (using LN2 as simulant) for extended duration in a simulated space thermal vacuum environment

Ensuring Information is Infused

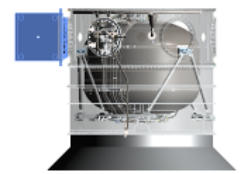
Tech Maturation



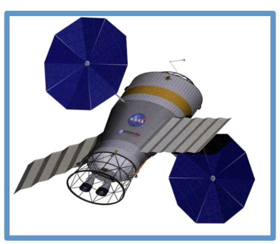
- **Industry Day Briefings** of Tech Maturation and as yet unpublished ETDP technology work
- **Technical reports** – TMs, Conference papers, Journal Articles
- **NASA analysis capability** developed/validated in parallel to benchmark contractor
- **Annual review** of technology maturation and payload development activities



CPST Flight Demo



NASA led Technical reports – TMs, Conference papers, Journal Articles
NASA analysis capability (tools and personnel) available to gov't systems development team and NASA owns data rights on **technology performance results, key technology details**.
Allows NASA to share technology with all interested parties.



Future Systems (CPS)

Flight Demonstration Closes CFM Technology Gaps

- Primary motivation for the CPST technology demonstration mission is to enable long duration beyond LEO human exploration missions (Moon, NEA & Mars)
  - A Cryogenic Chemical (LOX/LH2) Propulsion Stage (CPS), capable of storing and transferring cryogenic propellants is considered **required** for all such missions.
- Closing the technology gaps *requires* microgravity environment and opens the trade space for future missions.
  - **Required** to demonstrate thermal and pressure control performance for long duration storage
  - **Required** to demonstrate LAD performance for vapor-free liquid acquisition and transfer
  - **Required** to validate microgravity mass gauging systems
- Propulsion applications require a flight demo to address *both* storage & transfer.
  - Must repeatedly get liquid (not pressurant gas) out of the tanks in space
  - Must verify that fluids leaving the tank are gas-free liquids
  - Verify quantities of fluids on orbit, settled or unsettled

A flight demonstration is the only way to close CFM technology gaps and ready the Cryogenic Propulsion System for future in-space applications.

Back-Up

LH2 Active Cooling – Thermal Test

Objective:

Demonstrate integration and system performance of a Broad Area Cooling (BAC) shield embedded in tank-applied thick Multi-Layer Insulation (MLI) cooled by a flight representative cryocooler

Key Accomplishment /Deliverable /Milestone:

- MLI blankets and the BAC shield were designed and assembled.
- Cryocooler Integration: Flight representative cryocooler integrated to BAC shield and flight-like radiator (cold and hot side tested). Actively cooled tank struts and plumbing.
- Completed test (Simulated space vacuum and thermal environment) in December 2012.

Significance:

- Enable reduced boil off on-orbit storage of liquid hydrogen using a 90K cryocooler-based active thermal control system.

Reduced LH2 Boil Off Test: inner MLI and BAC shield installed on the tank. "Sauna shield" for BAC shield bake out procedure installed.

MLI/BAC Shield Structural Integrity Test

Objective:

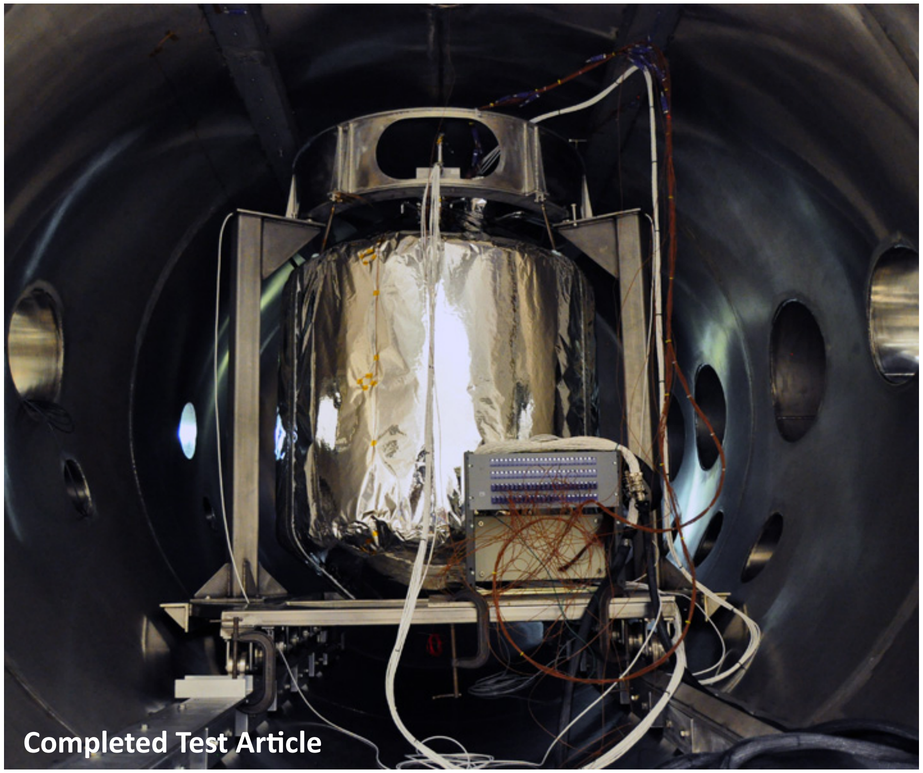
The Vibro-Acoustic Test Article (VATA) was built to structurally evaluate an integrated Multilayer Insulation (MLI) and and integrated Broad Area Cooling (BAC) Shield system.

Key Accomplishment /Deliverable / Milestone:

- MLI and BAC Shield Design and Assembly: MLI blankets and the BAC shield were designed by a multi-center team and built at MSFC.
- Thermal Test 1: A thermal test using LN2 baselined the system thermal performance prior to VATA acoustic testing. *Completed August, 2012.*
- Acoustic Test: VATA was be exposed to a simulated launch acoustic environment. *Completed early September, 2012.*
- Thermal Test 2: An identical test matrix was conducted to evaluate possible changes in the VATA thermal performance as a result of exposure to the acoustic load. *Completed September, 2012.*

Significance:

- Experience and data from VATA testing will inform design of future integrated MLI and shield systems.
- Design used for VATA proved to be structurally sound.



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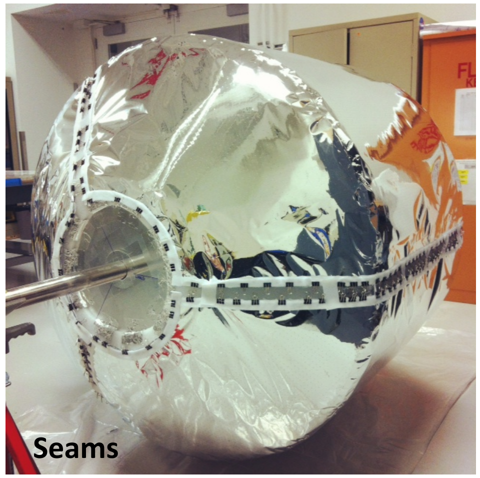
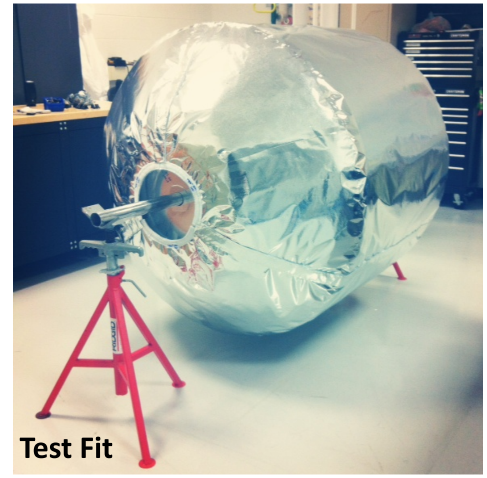
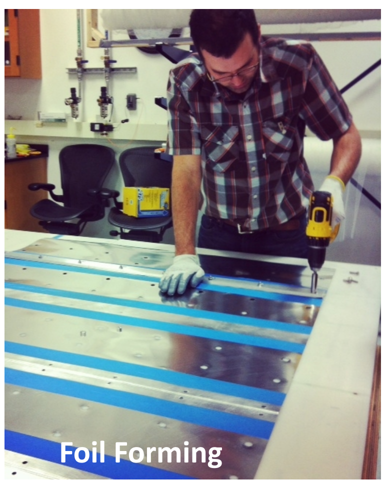
MLI/BAC Shield Thermal and Acoustic Test

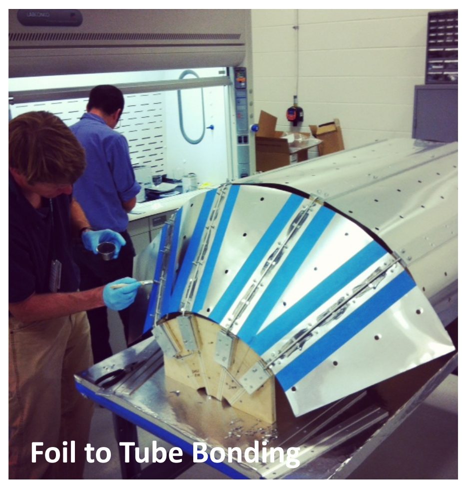
MLI Assembly

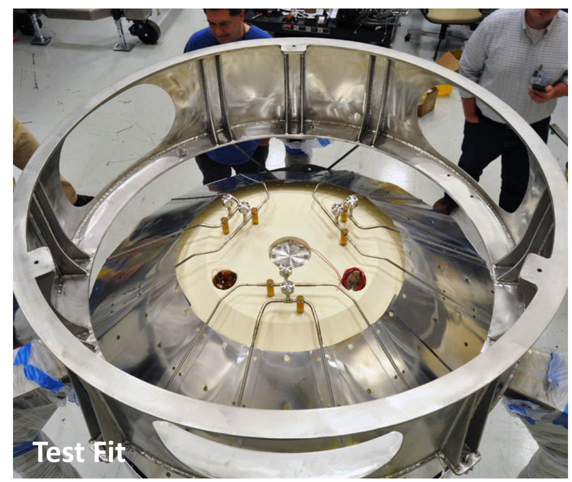




BAC Shield Assembly







LAD Outflow & Line Chilldown

Objective:

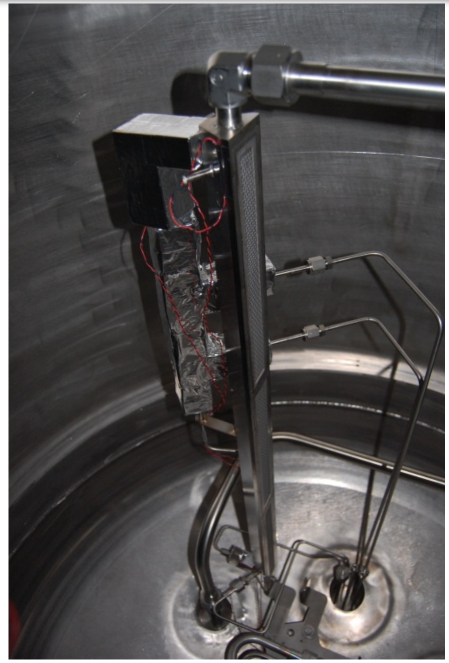
Quantify the LAD stability (no LAD breakdown) due to transfer line chill down transient dynamic pressure perturbations during outflow

Key Accomplishment /Deliverable / Milestone:

- Moved test article to Supplemental Multipurpose Research Facility (SMiRF) 5/25/2012
- Test Readiness Review 7/12/2012
- Liquid Hydrogen Test 7/31-8/23/2012
- Test Data Review planned 9/13/2012
- Preliminary Findings Report planned 11/20/2012

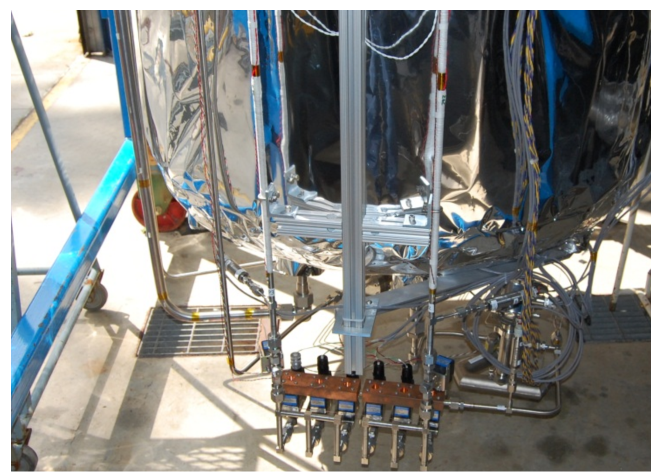
Significance:

- Completed over 100 flow through screen tests, as well as gaseous helium calibration, further analysis is required to eliminate anomalous tests from the results.
- Completed over 80 line chill tests, successfully ran 8 different pulse flow cases, and have identified the optimal valve duty cycle for this test configuration.
- Completed over 20 Inverted Outflow LAD breakdown tests; TVS cooled LAD shows superior performance



Flight Representative LAD Installed

Sight Glass during Line Chilldown (Multiple images as a function of time)

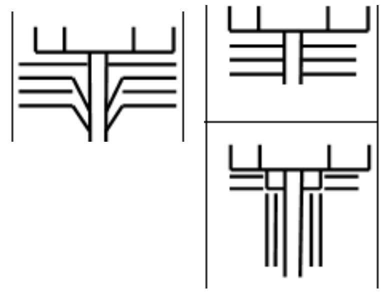


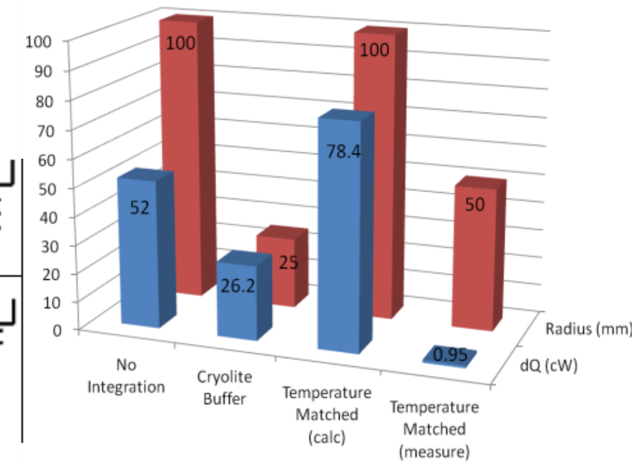
Line Chilldown Manifold and Line bottom

Penetration Heat Leak Study

Objective:

•Quantify thermal losses involving integrating MLI into real situations.
•Testing & Modeling specifically focused on the effects of penetrations (including structural attachments, electrical conduit/feedthroughs, and fluid lines) through MLI.





Comparison of Different Integration Approaches

Key Accomplishment /Deliverable / Milestone:

•Design, Fabricate, & Checkout calorimeter 9/30/11
•Finish 22 test cases & Test Data Review 5/25/12
•Final Report 9/30/12

Significance:

•Developed test method for measuring degradation of MLI around a penetration
•Measure heat load degradation and radius of thermally effected zone
•Determined the integration is best done with Cryolite microfiberglass blankets
•Built & validated detailed thermal model of penetrations
•Developing predictive relationships for penetrations based on model runs
•Integrated solution into Broad Area Cooling thermal and acoustic tests

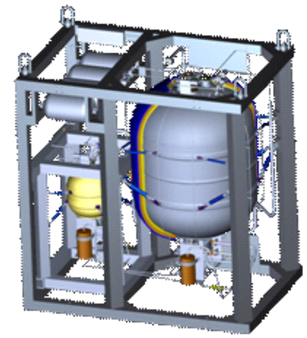
Testing at KSC and Integration into BAC testing at GRC

PI: Wesley Johnson, Key Personnel: Andy Kelly, Wayne Heckle

CPST Continuing Activities

Ground Test Article (GTA)

Objective: The GTA is a technology development version of the CPST Cryogenic Fluid Management (CFM) Payload that serves as a pathfinder for manufacturing flight hardware and for developing system operational procedures.



Integrated Technology Ground Test Article

Key Accomplishment /Deliverable /Milestone:

- Design is complete and hardware fabrication has started.

Significance:

- Investigate system interactions and identify design and control issues.
- Demonstrate flight tank prototype manufacturing and a streamlined engineering/manufacturing approach.
- Provide data to anchor models to support design and to build analytical models for scaling CPST to a "full-scale" application, to explore autonomous control of the CFM payload, and to characterize the rate of structural heat leakage for the integrated tank structures.

Composite Tank Strut Structural Test Configuration

Storage Tank Bottom Dome in Machining

Contoured LAD Channel Segment (with Screen) Weld Sample

Transfer Tank Dome ID Machining

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CPST Continuing Activities

Radio Frequency Mass Gauge

Objectives:

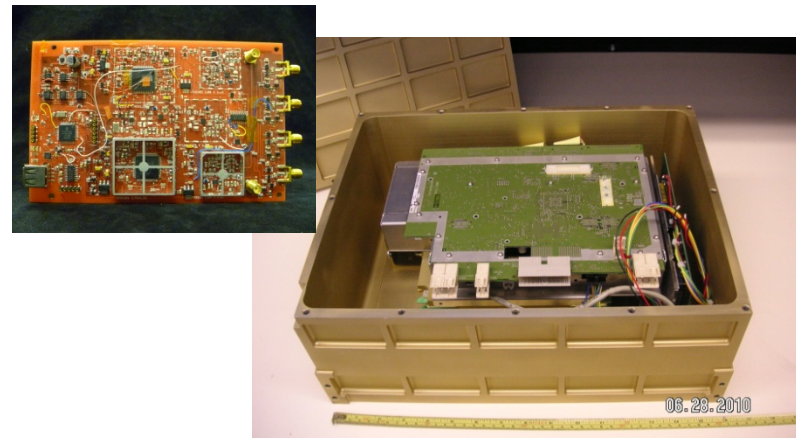
Develop RFMG electronics and hardware elements necessary to enable a spaceflight demonstration of the low-gravity Radio Frequency Mass Gauge. Conduct parabolic flight testing of the RFMG.

Key Accomplishment /Deliverable /Milestone:

- Through the OCT Flight Opportunities Program, conducted low-g aircraft testing of the RFMG in 2011 using an inert simulant fluid, FC-77
- Developed hardware/software for a future suborbital flight test (FY12)
- Conducted structural analysis, vibe testing, EMI testing of critical hardware components (FY12)
- Completed a rev2 design and fabrication of a custom RF Vector Network Analyzer card

Significance:

- Low-g aircraft tests provide critical data for testing and improving the RFMG performance
- Suborbital flight test in FY13 will provide RFMG data from a LOX tank on a flight vehicle
- Custom RF electronics card development has the potential to significantly reduce mass/power of avionics unit



RFMG Electronics Development

Low-g Aircraft Testing of the RFMG

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